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Furnace Blower Electricity: National and Regional Savings Potential

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ABSTRACT

Currently, total electricity consumption of furnaces is unregulated, tested at laboratory conditions using the DOE test procedure, and is reported in the GAMA directory as varying from 76 kWh/year to 1,953 kWh/year. Furnace blowers account for about 80% of the total furnace electricity consumption and are primarily used to distribute warm air throughout the home during furnace operation as well as distribute cold air during air conditioning operation. Yet the furnace test procedure does not provide a means to calculate the electricity consumption during cooling operation or standby, which account for a large fraction of the total electricity consumption. Furthermore, blower electricity consumption is strongly affected by static pressure. Field data shows that static pressure in the house distribution ducts varies widely and that the static pressure used in the test procedure as well as the calculated fan power is not representative of actual field installations. Therefore, accurate determination of the blower electricity consumption is important to address electricity consumption of furnaces and air conditioners.

This paper compares the potential regional and national energy savings of two-stage brushless permanent magnet (BPM) blower motors (the blower design option with the most potential savings that is currently available in the market) to single-stage permanent split capacitor (PSC) blower motors (the most common blower design option). Computer models were used to generate the heating and cooling loads for typical homes in 16 different climates which represent houses throughout the United States. The results show that the potential savings of using BPM motors vary by region and house characteristics, and are very strongly tied to improving house distribution ducts. Savings decrease dramatically with increased duct pressure. Cold climate locations will see savings even in the high static pressure duct situations, while warm climate locations will see less savings overall and negative savings in the high static pressure duct situations. Moderate climate locations will see little or no savings.

Introduction

This paper expands the work of an earlier ACEEE paper (Lutz et al 2006) that looked at the electricity consumption by Permanent Split Capacitor (PSC) and Brushless Permanent Magnet (BPM)[1] motors for a single house located in the Central Valley in California. The results showed that BPM motors outperform PSC motors, but the total electricity savings are significantly less than projected using the DOE test procedure conditions and the performance gains depend on the static pressure of the house ducts, which are typically much higher than in the test procedure. The authors suggested in their conclusions that further analysis was needed to

[1] BPM motors are also known as Electronically Commutated Motors (ECM) which is registered trademark of General Electric.

take into account various regional climate conditions and house characteristics. This paper does some of this further analysis.

This paper compares the electricity consumption of a PSC motor in a single-stage non-condensing furnace and a BPM motor in two-stage non-condensing furnace at a range of static pressures and various climate conditions. Single-stage non-condensing PSC motors are the most common furnace configuration (DOE 2007), while BPM motors are most commonly found in two-stage furnace configurations (DOE 2007; Habart 2005). We also enhanced and expanded the calculation approach by accounting for more accurate fan curves, air conditioner performance, different duct types, and system curves to be able to assess the performance of these motors in the houses with different heating and cooling requirements.

Furnace blowers distribute air throughout the house during both heating and air conditioning operation. Electricity use by blowers is currently reported as part of the Average Annual Auxiliary Electrical Energy Consumption (E_{AE}), which is a measure of the total annual furnace electricity consumption using the U.S. Department of Energy's (DOE) test procedure (DOE 2008) conditions and is used to calculate incentives for more efficient blowers (CEE 2007). Previous furnace blower studies using E_{AE} results show saving for BPM motors are between 48-67% (Kendall 2004; Sachs 2001; Sachs & Smith 2004; Sachs & Smith 2003). Yet, recent studies have shown that the electricity consumption determined using the test procedure does not accurately represent the electricity consumption of blowers installed in the field and that it varies with static pressure. (Lutz et al. 2006; Walker 2007) Lab tests for BPM motors in the heating season show 74% savings at low static pressure (Gusadorf et al 2002) while savings decrease to 48% at higher static pressures (Walker et al 2003). The same lab tests show blower motor cooling season savings of 48% at low static pressure (Gusadorf et al 2002) to essentially no savings at higher static pressures (Walker et al 2003). Field tests show a similar trend with average heating season savings of between 30 to 40% (Pigg 2003; Phillips 1998). Furthermore, various field studies have shown that the static pressure ranges from 0.3 to 1.2 in w.g. (Chitwood 2005; Phillips 1998; Pigg 2003; Wilcox 2007), which is much higher than what is used in the DOE test procedure. Therefore, some studies suggest that blowers are not adequately rated using the test procedure and that blower motors should be rated at 0.5 to 0.8 in w.g (Phillips 1998; Sachs & Smith 2004; Walker et al 2003; Walker 2007). Furthermore, during the recent Energy Star furnace rulemaking, several stakeholder comments pointed to the fact that further research was needed to ensure the energy savings of BPM motors. (EPA 2006, EPA 2007)

Methodology

This paper calculates the electricity consumption of furnaces with PSC and BPM motors under three different field conditions that represent a range of static pressure in the existing vent distribution systems at 16 different house locations in the U.S. The calculation methodology is similar to the one used in the previous ACEEE paper (Lutz et al 2006), but has been enhanced and expanded to account for more accurate fan curves, air conditioner performance, different duct types, and system curves.

Household and Equipment Characteristics

In the DOE test procedure, the heating requirements are calculated using the Design Heating Requirement (DHR) and average conditions for the United States. We used DOE-2 models to derive the hourly heating and cooling requirements for prototypical houses in 16 locations. The models represent typical construction practices in the Northeast, North Central, South, and West regions of the country. House characteristics, the average heating load, and average total cooling load are shown in Table 1. The details of the prototypical houses are described in Huang, et al. (Huang et al. 1999)

Table 1: Household Characteristics from DOE-2 and Selected Furnace Characteristics

Location	Square Footage (feet^2)	Foundation Type	Average Heating Load (MMbtu/yr)	Average Cooling Load (MMbtu/yr)	Furnace Capacity (kBtu/h)	Cooling Capacity (AC Tons)
Albuquerque, NM	1844	slab	12.1	12.3	70	3
Atlanta, GA	2053	crawl space	13.6	29.1	80	3
Boston, MA	2197	basement	44.1	9.4	90	3
Chicago, IL	3178	basement	88.1	13.9	140	4
Denver, CO	2146	crawl space	71.3	3.6	70	3
Fort Worth, TX	2361	slab	9.6	41.7	80	3
Kansas City, KS	2768	basement	80.8	11.7	120	4
Los Angeles, CA	2386	slab	1.4	1.2	45	2
Miami, FL	1724	slab	0.2	42.3	45	2
Minneapolis, MN	3016	basement	148.0	0.7	140	4
New Orleans, LA	2361	slab	4.6	47.5	75	3
New York, NY	3156	basement	66.5	17.4	140	4
Phoenix, AZ	1845	crawl space	8.9	48.6	70	3
San Francisco, CA	2386	slab	7.4	0.5	60	2
Seattle, WA	1721	crawl space	23.3	0.5	50	2
Washington, DC	2242	crawl space	45.7	13.8	70	3

In this study, we considered a non-condensing non-weatherized gas furnace (80% AFUE) with either PSC motor type with single stage controls or BPM motor type with two-stage controls. We assigned the furnace capacity to each house by calculating the maximum heating load and applying an oversizing factor of 1.7. (DOE 2008) Commonly available furnace sizes, (DOE 2007) with an output capacity above this oversized heating load, were selected for each house. The maximum and minimum nominal blower size available for each furnace varies by furnace capacity. (DOE 2007) This limits the actual range of air conditioner sizes that can be selected for the household. To select within this range we calculated the maximum cooling load and multiplied it by an oversizing factor of 1.1. The resulting furnace capacity and air conditioner size are listed in Table 1.

Energy Use Determination

The DOE test procedure calculates furnace electricity consumption during the heating season only, using burner operating hours and the power rating and operating time of electrical components. As in the earlier ACEEE paper (Lutz et al 2006), we calculated the hourly furnace electricity consumption during the heating season, the cooling season, and standby. Furnace electricity use is affected by operating modes that happen at the beginning and end of each furnace firing cycle. These operating modes include the pre-purge and post-purge by the draft inducer, the on-delay and off-delay of the blower, and the hot surface ignitor operation. To accurately calculate this effect, we calculated the hourly number of firing cycles for each of the 16 prototypical houses.

The electricity consumption of a blower motor depends on fan speed and the static pressure across the blower. Since the DOE test procedure calculates the furnace blower electricity consumption at a static pressure that differs from the actual field conditions (Pigg 2003; Phillips 1998; Chitwood 2005; Walker 2007; Wilcox 2007), we compared furnace electricity use for three different duct pressures types defined as follows: Ideal Ducts (based on the DOE test procedure conditions), Good Ducts (according to the manufacturer rating conditions), and Typical Ducts (based on average found in the field data). Fan performance data is based on manufacturer product literature in the Furnace Model Database. (DOE 2007) Table 2 provides a summary of the parameters and calculations used.

Table 2: Furnace Blower Electricity Parameter Summary Table

Location	Parameter Value	Source
Blower (Heating Season)	$ElectricityUse = BE * \left[BOH + Cycles * (t_{-} + t_{+})\right]$	(Lutz 2006)
Electricity Use (BE, BEr)	Intersection of fan curve and system curve (see Figure 1-2)	Calculated
On/off delay per cycle	on delay per cycle (t_+) =120 sec; off delay per cycle (t_-) = 25 sec	(DOE 2007)
Blower (Cooling Season)	$ElectricityUse = BE * COH$	(Lutz 2006)
Electricity Use (BE_C)	Intersection of fan curve and system curve (see Figure 1-2)	Calculated
Ignition Electricity Use	$ElectricityUse = PE_{IG} * Cycles * t_{IG}$	(Lutz 2006)
Electricity Use (PE_{IG})	400 watts	(DOE 2007)
on-time per cycle (t_{IG})	0.62 min	(DOE 2007)
Inducer Electricity Use	$ElectricityUse = PE * \left[BOH + Cycles * (t_P)\right]$	(Lutz 2006)
Electricity Use (PE)	75 watts, 75 * 80% watts for reduced mode	(DOE 2007)
pre-purge/post-purge (t_P)	30 seconds	(DOE 2007)
Electricity Use during Standby	$ElectricityUse = (8760 - BOH - COH) * PE_{standby}$	(Lutz 2006)
$PE_{standby}$	5 watts (PSC option); 9 watts (BPM option)	(Pigg 2003)
Burner Operating Hours (BOH)	$BOH = \dfrac{HeatingLoad}{Q_{IN} * AFUE + BE * 3.412}$	(Lutz 2006)
Input Capacity	Determined from oversized heating load and AFUE	Calculated
Reduced Input Capacity	Qin_r = .7 * Qin	(DOE 2007)
Cooling Operating Hours (COH)	$COH = \dfrac{CoolingLoad}{CoolingCap * Adj_{temp} * Adj_{CFM} - BE * 3.412}$	(Lutz 2006)
Cooling Capacity	From product literature (approx. 12 kBtu/h per AC ton)	(Carrier 2004)
Temperature/CFM Adjustments	Derived from Carrier Product Literature	(Carrier 2004)
Furnace Cycles	Calculated directly from DOE-2 hourly heating load data	(Lutz 2006)
Cycles per hour	5	(DOE 2008)
Fan Airflow and Power Curves	Derived average fan and power curves for each of the standard nominal blower sizes using manufacturer data. See Figure 1-2.	(DOE 2007)
System Curves	See Figure 1	(Lutz 2006)
DOE Test Procedure (Ideal Ducts)	0.18 for 2-ton AC, .20 for 3-ton AC, .23 for 4-ton air conditioner, and .28 for 5-ton AC at the nominal heating airflow.	(DOE 2008)
Manufacturer Ratings (Good Ducts)	0.5 in.w.g. at the nominal AC airflow.	(DOE 2008)
Field Data (Typical Ducts)	0.8 in.w.g. static pressure at nominal AC airflow	(Wilcox 2007)

The operating conditions for the 3-ton PSC and BPM blower motor at cooling mode are graphically displayed on Figure 1 as the intersection of the system curve of the ducts in the house with the fan curve of the furnace blower. Notice the static pressure for BPM blower motor is higher than the static pressure for the PSC blower motor on the typical ducts. The electricity consumption of the motor is shown in Figure 2. It represents the input power as a function of static pressure using the motor power curve. Intersection points are highlighted.

Figure 1: Intersection of System Curve and Fan Curve for 3-Ton PSC and BPM Blower Motors during Cooling Mode

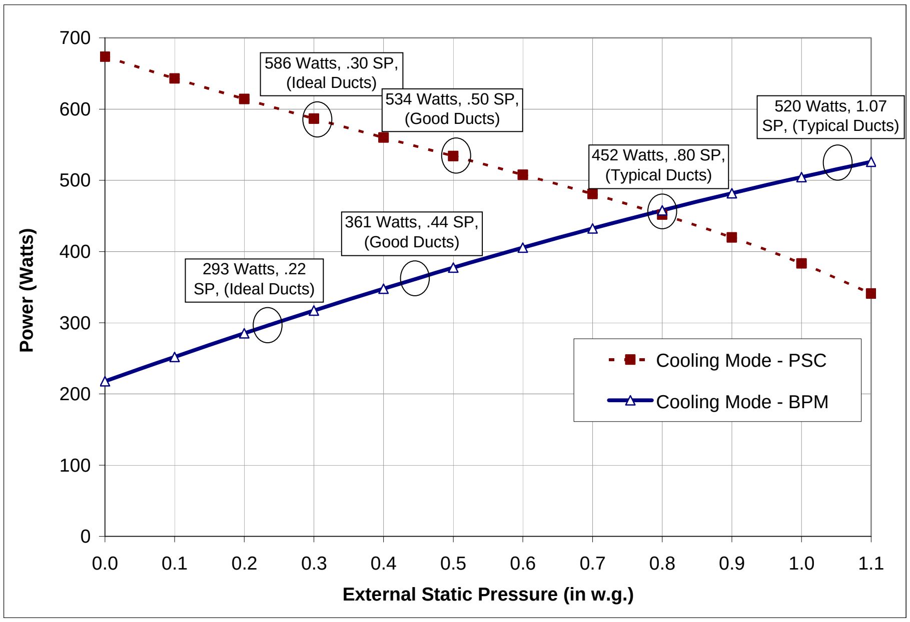
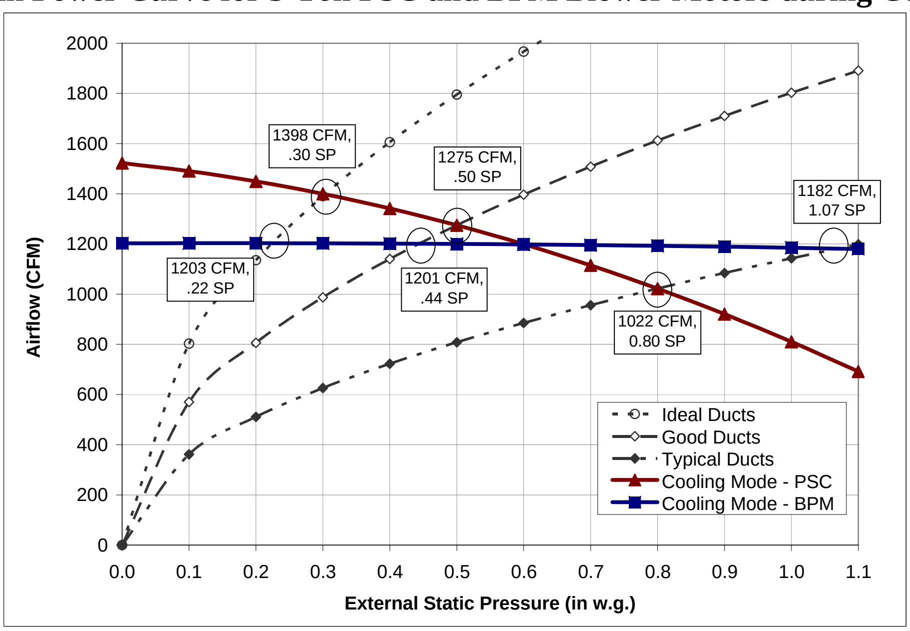


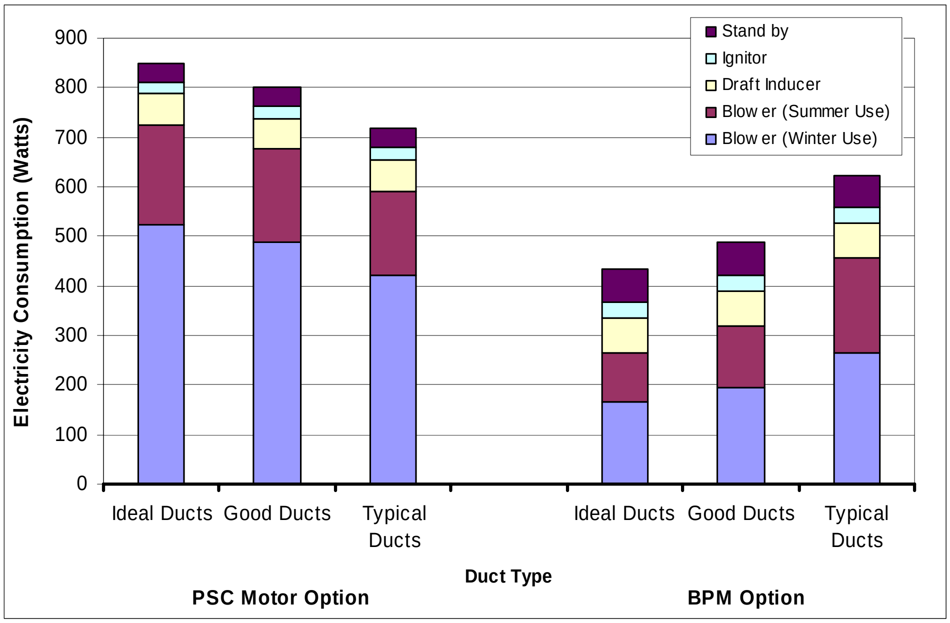
Figure 2: Fan Power Curve for 3-Ton PSC and BPM Blower Motors during Cooling Mode



Results

Our analysis uses a single-stage furnace with PSC blower motor (the most common configuration in today's furnace market) as a point of comparison to two-stage furnace with BPM blower motor. Figures 3 shows the electricity consumption component breakdown for the Chicago household using PSC and BPM design options under three duct types: ideal, good ducts, and typical ducts.

Figure 3: Electricity Use by Component in Chicago Household for PSC and BPM Options



For the Chicago household, PSC motor electricity consumption accounts for about 80% of total electricity consumption by the furnace and motor blower use during both winter and summer, while BPM motor consumption accounts for 60-70%. Standby consumption is not an insignificant amount, accounting for about 5% of PSC consumption and more than 15% in BPM. As observed in the previous paper (Lutz et al 2006), the overall savings decrease as duct pressure increases. The overall savings range from 49% for ideal ducts to 13% for typical ducts. The main reason electricity savings are smaller is that, to maintain constant airflow, BPM motors use more electricity as static pressure increases.

Table 3 gives a summary of the blower-only (without taking into account standby) savings ranges for all 16 household prototypes during the winter and summer. In general, the results show that blower-only winter electricity savings decrease as duct pressure increases. The blower-only winter savings decrease from 65-71% for ideal ducts to 26-39% for typical ducts. The blower savings during cooling also decrease with increased duct pressure. The savings are lower than blower heating savings and become negative with typical ducts. The savings vary from 45% to 51% for ideal ducts to -11% for typical ducts. Savings during cooling are lower since PSC motors are reasonably efficient (above 70%) when operating at high speed (cooling speeds), but efficiencies drop significantly when these motors operate at lower speeds. (DOE

2007) Meanwhile, BPM motors can operate at efficiencies above 80% across a very wide range of speeds. Cooling savings become negative at static pressures greater than 0.8 in. w.g., since the power draw of BPM motors is greater than that of PSC motors.

Table 3: Motor Performance (Electricity Savings Range for PSC vs. BPM blower motors)

	Ideal Ducts	**Good Ducts**	**Typical Ducts**
	% Electricity Savings	% Electricity Savings	% Electricity Savings
Blower Only - Heating	65 to 71%	56 to 62%	26 to 39%
Blower Only - Cooling	45 to 51%	29 to 33%	-11.2% to -10.7%

Figure 4 shows the total electricity consumption results for the PSC motor option, which includes blower electricity use in the winter and summer, inducer fan use, ignition use, and standby power, for the 16 household prototypes. As the figure shows the total electricity consumption varies widely depending on location and duct type. The electricity consumption varies from 82 to 1,055 kWh/yr for ideal ducts, 80 to 996 kWh/yr for good ducts, and 77 to 883 kWh/yr for typical ducts. As noted before, PSC motors use less electricity with increasing static pressure.

Figure 4: Total Electricity Consumption PSC Motor Option

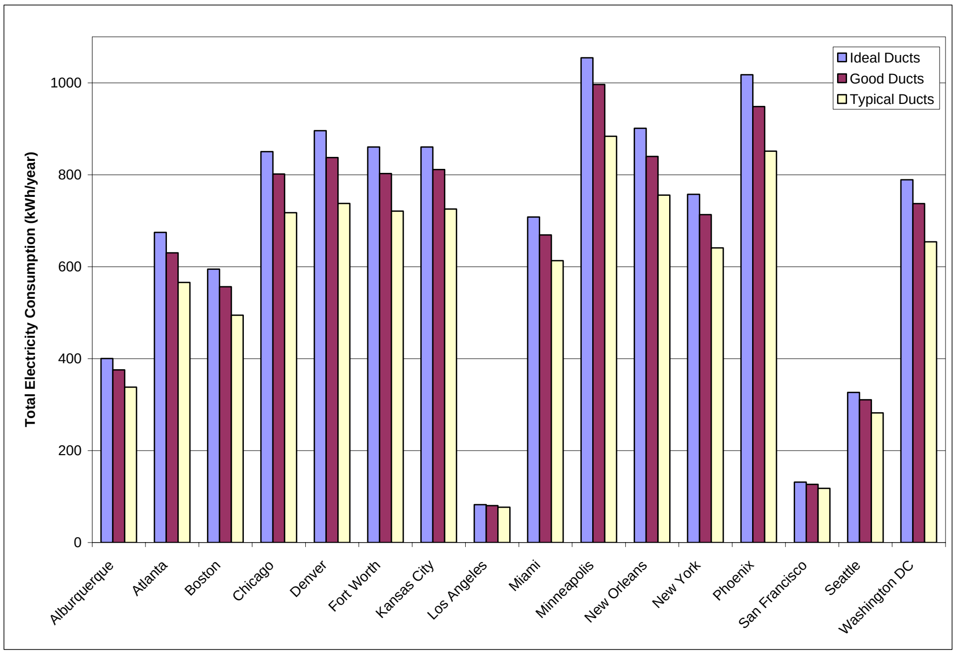


Figure 5 shows the total electricity consumption results for the BPM motor option for the 16 household prototypes. As the figure shows, the total electricity consumption varies widely depending on location and duct type. The electricity consumption varies from 99 to 554 kWh/yr for ideal ducts, 102 to 665 kWh/yr for good ducts, and 110 to 936 kWh/yr for typical ducts. As noted before BPM blower motors use more electricity with increasing static pressure.

Figure 5: Total Electricity Consumption BPM Electricity Option

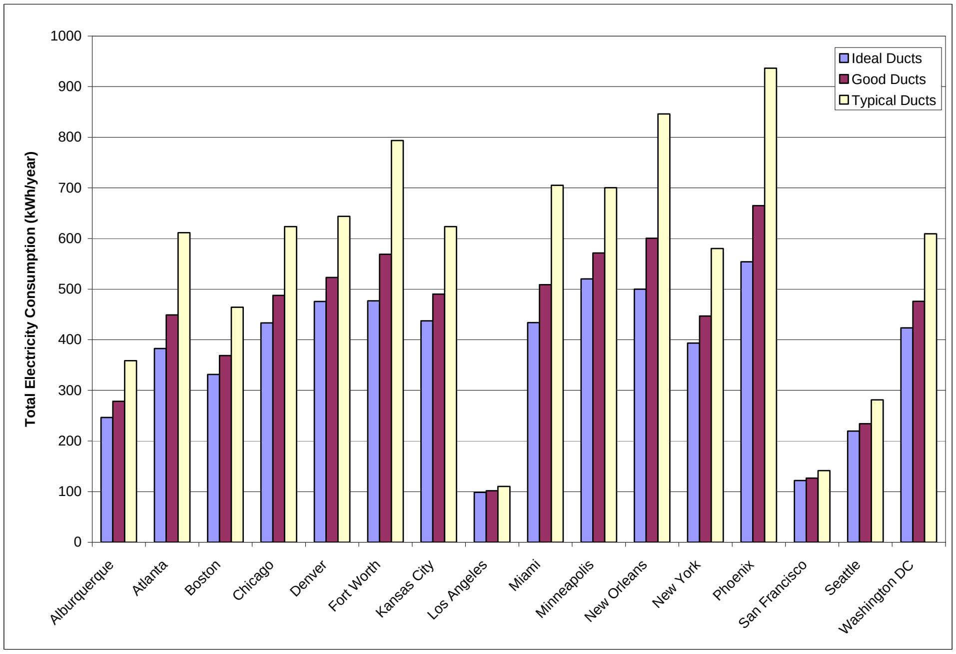
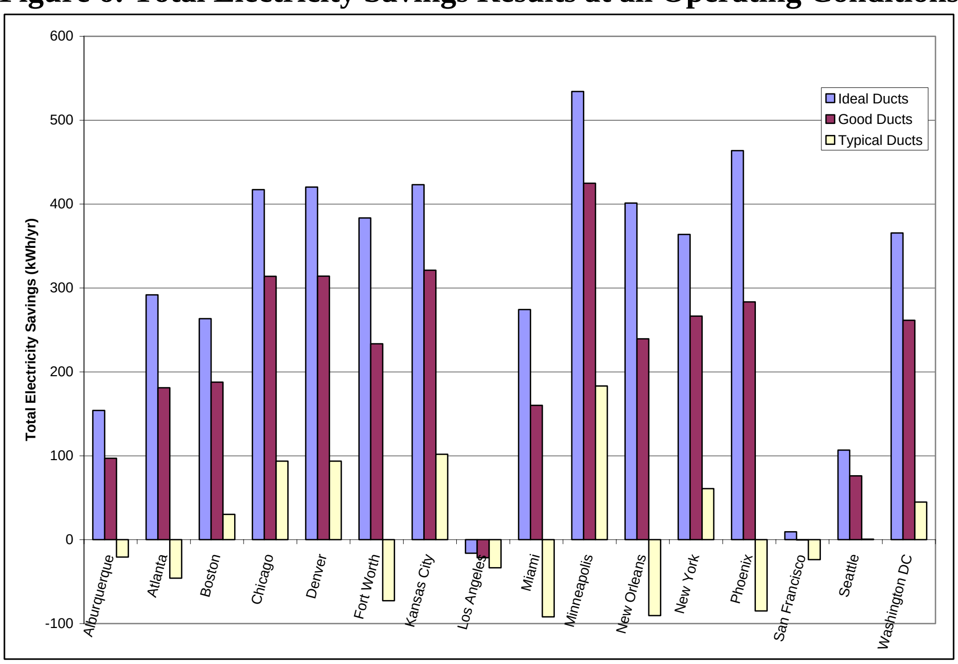


Figure 6 shows the overall electricity percent savings between the PSC and BPM motor options. The savings range from -16 to 534 kWh/yr for ideal ducts, -24 to 424 kWh/yr for good ducts, and -94 to 183 kWh/yr for typical ducts. The percentage savings range from -19% to 49% for ideal ducts, -26% to 39% for good ducts, and -44% to 21% for typical ducts.

Figure 6: Total Electricity Savings Results at all Operating Conditions



Overall electricity savings decrease with increased static pressure and vary widely with weather conditions. The results can be grouped into 3 household heating/cooling needs categories:

1) **Moderate Climate** (low heating/cooling needs) – Los Angeles and San Francisco;
2) **Warm Climate** (higher cooling needs or similar cooling and heating needs) – Albuquerque, Atlanta, Fort Worth, Miami, New Orleans, Phoenix;
3) **Cold Climate** (significantly higher heating than cooling needs) – Boston, Chicago, Denver, Kansas City, Minneapolis, New York, Seattle, and Washington DC.

For house prototypes with low heating and cooling needs (moderate climate), the savings are very low or negative mainly due to standby power losses which are greater than any potential savings from the BPM motors.

House prototypes with higher heating and cooling needs (warm and cold climates) have similar savings with ideal ducts and good ducts, but are quite different in the case of typical ducts. In the case of ideal ducts, warm and cold climate houses have similar electricity savings of 40-50%. Warm climate house savings are slightly lower 40-45% compared to 45-50% for cold climate houses. In the case of good ducts, warm and cold climate houses also have similar electricity savings. Warm climate house savings are slightly lower 23-30% compared to 33-43% for cold climate houses. In the case of typical ducts, there is a large difference in the results. Cold climate house savings are 5-21% compared to negative savings of -5% to -15% for warm climate houses.

Aggregated Regional and National Savings

To determine regional and national results we used the approach described in the LBNL report (Huang et al. 1999), which disaggregates the 16 household prototypes by census divisions and climate. Using RECS 2001, we assigned household weights to the individual households with gas furnaces only and households with both central AC and gas furnaces.

Aggregated regional results by the 3 categories and national results are shown in Table 4. Results are weighted by RECS 2001 and take into account houses with and without central AC units. Regional results are grouped into the three categories described in the previous section.

Table 4: Regional (3 categories) and National Results by Duct Type

	RECS	**Ideal Ducts**			**Good Ducts**			**Typical Ducts**		
	% of House holds	Electricity Consumption (kWh/yr)		% Saved	Electricity Consumption (kWh/yr)		% Saved	Electricity Consumption (kWh/yr)		% Saved
		PSC	**BPM**		**PSC**	**BPM**		**PSC**	**BPM**	
Moderate Climate	12%	140	126	9%	134	132	2%	125	148	-19%
Warm Climate	27%	619	345	44%	578	400	31%	518	538	-4%
Cold Climate	62%	673	356	47%	634	399	37%	567	509	10%
National Results	100%	662	361	45%	623	407	35%	559	523	6%

House prototypes with low heating and cooling needs (moderate climate) show savings of only 9% with ideal ducts, 2% with good ducts, and -19% with typical ducts. Warm climate houses have savings of 44% with ideal ducts, 31% with good ducts, and -4% with typical ducts. Cold climate houses have savings of 47% with ideal ducts, 37% with good ducts, and 10% with typical ducts.

Nationally, two-stage furnaces with BPM blower motors consume 45% less electricity with ideal ducts, 35% less electricity with good ducts, and 6% less electricity with typical ducts compared to single stage furnace with PSC blower motors.

Study Limitations

In this paper, we tried to account for many secondary effects of switching from a PSC to BPM motor option. Yet, there are some effects which require further research (e.g. effects of changes in airflow on furnace efficiency), need more data (e.g. demographic trends), or are beyond the scope of this paper (e.g. non-fan blower AC electricity consumption).

We assume that the blower distributes airflow evenly throughout the household and all loads are adequately met, but in the field this might not be true. Some remote areas of the household might be starved of airflow by using furnaces with a PSC motor at high pressure. Furnaces with BPM motors may be able to maintain adequate airflow rates to meet the heating/cooling demands in exchange for under delivering on energy savings. Yet, a two stage furnace might not work as well in large complicated home with large duct systems, since at lower motor speed it may not have an adequate blower speed to push air to all parts of the home.

In this study, we also did not account for the following:

- Changes in fuel consumption due to decreased electricity consumption (Gusdorf et al. 2002).
- Low-speed fan only operation of the furnace blower fan, which could lead to significant savings for BPM motors (Pigg, 2003).
- Non-fan blower AC electricity consumption, which could be a significant effect since there are differences in cooling operating hours between PSC and BPM blower motors.
- Condensing furnaces (which are more than one-third of shipments) would reduce burner operating hours and therefore also reduce potential electricity savings for BPM motors.
- Use of a variable speed blower with a multiple speed AC compressor, which could lead to significant savings for BPM motors.
- Possible changes in furnace efficiency with airflow lower than test procedure conditions.
- Demographic and new construction trends, which have seen a shift towards the south and west; the California locations in this study have milder climates than where new construction is occurring.
- Use of time delay relay for summer blower use which could increase blower operating hours and therefore increase BPM motor savings.

Conclusion

In this study, we compared the electricity consumption of residential non-condensing, non-weatherized gas furnaces with two-stage BPM blower motors to the single-stage furnaces with PSC motors for 16 house prototypes with three duct types (ideal, good, and typical ducts).

The results indicate electricity savings from BPM motors are climate dependent and vary with duct pressure. Savings decrease with increased duct pressure. Furthermore, houses with low cooling and heating loads (moderate climate) will see little or negative savings. Warm climate houses will see lower savings than cold climate houses. In fact, warm climate houses with typical ducts may see negative savings. The majority of houses are in cold climate locations, which will see savings even in the typical ducts situation. Nationally, two-stage furnaces with BPM blower motors consume 45% less electricity with ideal ducts, 35% less electricity with good ducts, and 6% less electricity with typical ducts compared to single stage furnace with PSC blower motors.

Standby power consumption in furnaces with BPM blower motors is significantly higher than for furnaces PSC blower motors and in moderate climates can be more than the potential savings from BPM blower motors.

Overall, it appears the BPM blower motors used in two-stage furnaces offer national electricity savings, but with typical ducts the savings are much smaller than estimated with ideal ducts and good ducts. To have significant savings, a furnace with a BPM blower motor needs to be installed in a house with low pressure loss distribution system.

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